[Proc. Roy. Soc. Victoria, 37 (N.S.), Pt. II., 1925.

Art. XIV.—*Contact Metamorphism in the Bulla Area and Some Factors in Differentiation of the Granodiorite of Bulla, Victoria.*

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(With Plate XXVII.)

[Read 11th December, 1924.]

Contents.

1—General Geology.

The Geology and Physiography of the Bulla area have been described by Mr. A. V. G. James.[1]

The oldest rocks outcropping are Palaeozoic mudstones, with minor sandstones and conglomerates. These may include rocks of both Upper Ordovician and Silurian age. Lithologically there is no well defined difference between the two series, and both have probably been derived from the same land mass. Similar rock types are derived from both series by contact metamorphism. The beds dip steeply to the east and strike generally about N. 15°E. (magnetic bearing). Intrusive into these sediments is a mass of granodiorite, presumably Lower Devonian in age. This mass extends beneath later basalt flows north-eastward through Broadmeadows to Somerton and Craigieburn. The intrusion took place without contortion of the sediments, and caused the formation of contact rocks, which form the subject of the first part of this paper. The granodiorite is much decomposed everywhere on the surface exposures, although fairly fresh in the bed of Deep Creek. Blocks of the fresh rock have been blasted out on the western bank of the stream about half a mile south of the school.

Cainozoic sediments are found in various parts of the area, and much of the area has been covered by Newer Basalt.

Deep Creek has cut a deep trench through the younger rocks, and has exposed the Palaeozoic rocks and rocks of the contact zone. These latter are best studied along the northern side of the meander, a mile south of Bulla, as here the greatest variety of rock types is found, and the strike of the beds runs nearly at right angles to the boundary of the granodiorite. Poorer sections are seen on the northern bank of the east-west sweep of the river, about half a mile north of Bulla, and on the hillside opposite the school.

The locations of features mentioned in this paper are illustrated on a map enlarged from portion of James's map to which minor alterations have been made. The quartzite (Q) and sericite-rich band (S) have been added. From the general strike of the rocks, conglomerates C_3 and C_4 of James's map are the same bed, and the placing of C_3 directly south of C_4 is incorrect. The shape and location of the Hanging Valley are incorrect, and the conglomerate C_4 does not pass northward under basalt, but may be traced to within two chains of the contact of the granodiorite, against which it abuts, as shown in the accompanying map. James considers that the rocks west of C_1 (seen on Jackson's Creek, south-west of the Bulla meander) are Upper Ordovician. There is a band of white sandstone here at the same distance east of C_1 as the quartzite is east of C_3-C_4 on the Bulla meander, and the thicknesses of sandstone and quartzite respectively are approxi-

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1.—A. V. G. James. Proc. Roy. Soc. Victoria, Vol. XXXII. (N.S.), Pt. II., 1920.

mately the same. There is reason to believe that the quartzite is the northern prolongation of the sandstone, and therefore that C_3-C_4 is the northern prolongation of C_1. On these grounds the Palaeozoic rocks west of C_3-C_4 are marked on the map as Upper Ordovician. There appears to be a thinning out of the conglomerate northwards, and this may account for the absence in the Bulla meander area of the equivalent of C_1, on James's map, which appears only as a thin band on the Jackson's Creek section.

2—Contact Metamorphism.

A. General Character of Contact Zone.

The contact zone is variable in width, but on the average extends about a quarter of a mile from the actual contact. The change to unaltered rock is rather abrupt. The mudstones grade into an indurated, darker, uncleaved spotted rock, which in turn grades into the characteristic dark blue dense hornfels of the inner zones. The quartzites, of which there are two bands just east of the mouth of the Hanging Valley, show induration at a considerable distance from the contact, where they are grey in colour, and at the contact zone they become very massive and pink in colour. The sericite-rich bands, the largest of which is that shown in the map as S, do not change much in physical character by metamorphism.

B. Rock types found within the Contact Zone.

(i.) *Cordierite-Biotite-Quartz Hornfels.*—These form the bulk of the altered rocks. They vary according to the relative amounts of the three main constituents. Types rich in cordierite macroscopically appear fine-grained, and have a resinous lustre; types rich in quartz are coarser in grain. The former are abundant on the neck of the meander, the latter occur close to the conglomerate. The typical hornfels is intermediate between the two extremes, and is well represented along the cliff west of the mouth of the Hanging Valley.

(*a*) Original sediment from which the hornfels has been derived. [1630].[2]—This consists of quartz grains set in a fine matrix of sericite, chlorite and iron ore. There are occasional grains of apatite and zircon, prisms of tourmaline and needles of rutile.

(*b*) Transitional types.—The least altered rock [1631] shows a trace of clotting of the minerals seen in the unaltered rock, but in addition secondary biotite appears. This is a quartz-rich type collected from a bed adjacent to the quartzite on the southern bank of the southern side of the meander.

Transitional types of rock, which on complete recrystallization give cordierite-rich types, are found further down-stream on the

2.—Numbers in brackets refer to rock-sections in the collection of the Geological Department, University of Melbourne.

northern bank of the next meander. [1632, 1633, 1634.] Clotting is well developed in these. The clots are green in colour, and surrounded by lighter areas. In the lighter areas biotite is developed, the various degrees of development being seen progressively in the three sections. In the most altered type [1634] its development is almost complete. Accessory minerals are similar to those of the unaltered rocks. This type of clotting in which no new minerals are developed has been referred to by other writers,[3] and has been put down to solution effects. It may be readjustment of phases in response to higher temperature conditions.

(*c*) Recrystallized types.—Cordierite-rich types [1635 and 1640] show large anhedral patches of cordierite surrounded by a fine-grained mass of biotite flakes, quartz and cordierite grains. These large cordierite patches are full of inclusions of very small flakes of biotite and accessory minerals. By their relation to the ground mass they are clearly derived from the green clots, and they show no parallelism of arrangement. Sections [1634 and 1635] are from rocks only 15 yards apart, so that it would appear that once started, the development of cordierite is rapid.

The typical hornfels [1636], collected from the southern bank of the northern side of the main meander, shows less cordierite, with more quartz and biotite. The cordierite is clearer and the other minerals are better developed. The texture is granoblastic, but cordierite tends to enclose rounded grains of recrystallized quartz. There is a little secondary tourmaline.

(*d*) Inner Contact Zone types.—Rocks from the inner zone [1637-1639 and 1642-1644] are similar to the recrystallized types, but contain in addition grains of alkali felspar and flakes of muscovite. A siliceous type [1645], in which original quartz grains are left after recrystallization, has a grain of plagioclase felspar in it. This may be an original grain in the sedimentary rock. The actual contact hornfels [1639] possesses numerous grains of alkali felspar, and flakes of muscovite, while the cordierite is partially sericitized. Fully recrystallized hornfels lacking felspar and muscovite may be obtained at a distance away from the contact, so that these minerals appear to be characteristic of any line of strike within the inner contact zone, as all the collections were made at different points along the contact and as close to it as possible; therefore, it seems probable that these minerals are secondary.

(ii.) *Sericite-Biotite-Quartz Hornfels.*—These are grey in colour and have not the hardness of the cordierite-biotite-quartz hornfels. A specimen from the wide band previously mentioned, in thin section [1646] is seen to consist of round quartz grains set in a mass of more or less recrystallized sericite. The similarity of this sericite matrix to poikiloblastic cordierite of the cordierite hornfels might indicate that this type is an alteration product of

3.—C. E. Tilley: "Contact Metamorphism in the Comrie Area." Quart Journ. Geol. Soc., Vol. LXXX., Part I., 1924.

the cordierite hornfels, but the junction with typical hornfels of the latter on either side along the strike does not favour this view; moreover the biotite shows no trace of alteration.

(iii.) *Quartzites.*—Two sections [1647 and 1648] have been cut from the bands shown on the map as Q, at positions on the southern and northern sides of the meander respectively. These bands are lost under the basalt immediately south of the meander, but as indicated earlier their unaltered equivalents are found as white sandstones in the Jackson's Creek section. They are almost pure quartz rocks, but contain a little iron ore and sericite.

In the grey quartzite [1647] from the more southern exposure, the ore mineral is magnetite, while in the pink rock [1648] of the contact zone it is hematite to which the colour of the whole rock is due. The sericite is recrystallized in the latter. Lines of bubbles and inclusions pass through the rock irrespective of quartz grains. There is no siliceous binding material, and strength is evidently due to the interlocking of grains.

(iv.) *Amphibole Hornfels.*—These are rare, and appear to occur only in one or two beds of pale green, highly siliceous hornfels close to the altered conglomerate, and in parts of the matrix of the conglomerate itself. In the former occurrence [1649], the amphibole is a green variety, occurring with biotite in the ground mass surrounding unaltered quartz grains. In the matrix of the conglomerate [1650] the amphibole is in the form of pale green needles having an extinction angle of about 16°. It is, therefore, probably actinolite. Part of the section shows a pebble of quartz porphyry. Most of the pebbles of the conglomerate, however, are of quartzite or chert.

(v.) *Cordierite-Biotite-Quartz Hornfels modified by the introduction of alkaline material.*—This alkaline material threads its way irregularly through the hornfels as a vein, and on each side of the vein the hornfels is seen to have large crystal surfaces, typical of felspar, within it. The first example [1653-1657] was found on a boulder embedded in the sand at the foot of the mouth of the Hanging Valley, while, later, a similar type of rock was found *in situ* directly above the first example on the top of the cliff. The two occurrences may in reality be the same, but in the latter case the impregnation in the hornfels is more widespread.

The vein itself [1653] consists of acid felspars, probably orthoclase and oligoclase, which include small rectangular flakes of biotite, magnetite aggregates pseudomorphous after biotite, grains of an isotropic serpentinous mineral, plates of tourmaline enclosing rounded quartz grains, and quartz grains of various sizes. Muscovite flakes are also abundant, and are quite distinct from sericite derived from the felspars by normal weathering processes.

This vein junctions irregularly with altered hornfels [1654 and 1655], which is full of felspar acting as a base for biotite, quartz, muscovite, and sericitized and serpentinized cordierite. Tourmaline occurs in plates, perforated by other minerals, and, like the felspar, is clearly introduced.

Further away from the vein [1656] cordierite, only partially sericitized, appears, while the hornfels only slightly affected [1657] is strikingly similar to the contact zone hornfels [1639]. Thus it would appear that this vein of alkaline minerals represents an intense form of the introduction of felspar and muscovite characteristic of the inner contact zone hornfels. The minerals were probably deposited from a very fluid, highly aqueous differentiation product of the magma, which made its way by reaction with the hornfels rather than by forcing its passage. This reaction phenemenon will be discussed later.

(vi.) *Lime-silicate Hornfels.*—These occur as white or cream-coloured lenticles in the cordierite-biotite-quartz hornfels between the quartzite and conglomerate on the cliff west of the mouth of the Hanging Valley. Their unaltered equivalents have not been found, but are probably calcareous concretions. They are banded on their exterior, the bands being distinct from each other, while the outermost band, although somewhat resembling the ordinary hornfels, is distinct and the junction is abrupt.

Generally speaking, the mineral associations are similar. The outer bands [1661, 1664, 1669] are characterised by actinolite, which is present as needles often arranged in stellate fashion. Quartz is always present, and in one case [1661] there is a fine-grained mass of colourless mineral with a refractive index between that of quartz and actinolite, and showing low polarization colours. This mass contains occasional twinned basic plagioclases, and probably consists of this mineral itself. Pyrrhotite is an abundant mineral of the outer bands of some of the lenticles [1669]. This mineral is characteristic of all the altered rocks at Bulla, and may be due to the combination of sulphur bearing salts with iron during metamorphism.

In the next bands diopside appears, usually first as a fine-grained mass and later as crystals. Plagioclase may remain, but amphibole disappears. A few crystals of zoisite occur [1661], and also a cloudy mineral having a refractive index intermediate between quartz and diopside, and birefringence comparable with that of diopside. The sections of the interior of two lenticles [1662 and 1663] consist of diopside, quartz and this cloudy mineral. Other lenticles which probably had less free quartz originally [1664, 1665, 1666, 1667] consist of small diopside grains set in a mass of mineral which makes up much of the rock. This mineral is divided into what appears to be prismatic crystals, oriented more or less in one direction. The following optical properties have been determined:—

(i.) Straight extinction along a cleavage, seen in crystals exhibiting the higher polarization colours.

(ii.) Biaxial; positive; elongation negative.

(iii.) Birefringence comparable with diopside.

(iv.) Medium refractive index, but less than diopside.

(v.) Oriented with acute bisectrix perpendicular to the cleavage plane.
(vi.) Colourless; non pleochroic.

The mineral is evidently orthorhombic and prehnite, $H_2Ca_2Al_2(SiO_4)_3$, corresponds optically. The typical rosette structure of prehnite is absent, however, although in one occurrence [1668] the mineral occurs in leafy aggregates.

Calcite is present in the interior of the basic lenticles, and in one a vein of pure recrystallized calcite has been observed.

The cloudy mineral of the other sections [1662 and 1663] may also be prehnite, but optical properties cannot be easily determined.

C. Relation of Chemical Composition to Mineral Content.

(i.) *Cordierite - Biotite - Quartz and Sericite - Biotite - Quartz Hornfels.*—No analyses of these types from Bulla have been made, but the first-named is probably typical of its class, and the following analysis used by Tilley[4] would represent approximately the composition:—

SiO_2	- -	59.83
Al_2O_3	- -	17.47
Fe_2O_3	- -	4.09
FeO	- -	3.93
MgO	- -	3.70
CaO	- -	0.49
Na_2O	- -	1.08
K_2O	- -	4.42
H_2O	- -	3.80
TiO_2	- -	0.93
P_2O_5	- -	0.18
SO_3	- -	0.13
		100.05

Tilley gives certain theoretical equations for the formation of biotite and cordierite from sericite and chlorite.

$$K_2H_4Al_6Si_6O_{24} + 6FeO + 3SiO_2 = K_2H_4Al_6Si_6O_{24}\ .3Fe_2SiO_4.$$

Sericite. Iron ore. Quartz. Ferrous biotite.

$$K_2H_4Al_6Si_6O_{24}+2H_4Mg_3Si_3O_9=K_2H_4Al_6Si_6O_{24}.3Mg_2SiO_4+SiO_2+H_2O.$$

Serpentine molecule of chlorite. Magnesian biotite.

$$4K_2H_4Al_6Si_6O_{24}+6H_8Mg_5Al_2Si_3O_{18}+9SiO_2=4K_2H_4Al_6Si_6O_{24}.$$
$$.3Mg_2SiO_4+24H_2O+3Mg_2Al_2Si_5O_{18}$$

Cordierite.

4.—Op. supra cit.

If biotite and cordierite were minerals of fixed composition, then, unless the relative amounts of sericite and cordierite in the original sediments remained constant, additional minerals would have to appear. Among the Bulla contact rocks of this type, the minerals cordierite, biotite, quartz, only appear in the perfectly recrystallized rock. The variation in original chemical composition of the sediment is taken up by isomorphous mixtures in the hornfels minerals. Thus MgO and FeO vary in biotite and cordierite; Al_2O_3 and Fe_2O_3 in biotite; and the proportion of salic to femic constituents in the biotite. If chlorite rises in proportion to sericite, alkali will be lower, and hence cordierite will rise in proportion to biotite.

If sericite rises in proportion to chlorite, cordierite diminishes till finally it disappears, and, with sericite the dominant constituent of the sedimentary rock, sericite-biotite-quartz hornfels results. The elimination of sericite and chlorite gives first the quartz rich type and in the extreme case quartzite.

(ii.) *Amphibole Hornfels and Lime-silicate Hornfels.*—The amphibole of the former may be due to the presence of a small amount of lime in the original sediment.

In the latter, the various bands indicate an increase in lime towards the centre of the lenticle, with a relative decrease of alumina and magnesia. Amphibole and plagioclase take the place of biotite and cordierite in the outermost band, amphibole then disappears, and diopside with a higher CaO: MgO ratio appears. Finally prehnite (?) and recrystallized calcite are found in the centre of the lenticle.

D. Factors Producing Metamorphism.

Compared with the effects of certain other contact alterations in Victoria, the metamorphism at Bulla seems to be excessive when the size of the granodiorite intrusion is considered.

Pneumatolysis does not appear to have played a very important part in the process of recrystallisation, as minerals associated with pneumatolytic action are rare; tourmaline is, in fact, the only one present, and then not in great quantity. Furthermore, the effects of impregnation of hornfels with alkaline solutions containing tourmaline, and doubtless associated with the last stages of crystallization of the magma, occurred after the fundamental recrystallization which formed the hornfels, and have destroyed this fundamental recrystallization by decomposing biotite and cordierite, rather than perfecting their development.

It would seem that the nature of the sediments themselves plays an important part in effecting the metamorphism. At Bulla the sediments consist largely of hydrated minerals and minerals having diverse composition, viz., sericite and chlorite. The water of these sediments would have its solvent and chemical powers considerably increased by heat, but solution has acted only within a limited range, as variation of texture and composition of individual strata are sharply preserved in the recrystallized rock. [1641.]

Goldschmidt[5] considers that dry reaction of minerals in the solid state is the main process in metamorphism, in the case of the rocks of Christiania, Norway. This process is probably important at Bulla, and, just as in silicate melts the melting points of the individual components are lowered by the presence of other components, so with systems reacting in the solid state, the ease with which new minerals form, is increased by the heterogeneity of the reacting mass. The intimate nature of the mixture of sericite and chlorite would also help in furthering reaction.

Probably the best suite of contact rocks in Victoria occurs at Mt. Tarrengower, Maldon, and here the hornfels are similar to (though even better developed than) the Bulla hornfels. At Trawoöl are contact rocks which show cordierite-biotite-quartz [1651] and sericite-quartz [1652] hornfels alternating. The effects appear to have been greater in intensity and distribution in the former type than in the latter.

It is probable that active invasion of the wall rocks by an intrusive magma will have stopped before complete solidification, so that after this stoppage the residual heat of the magma is disseminated through the same sediments instead of repeatedly fresh ones, thereby allowing more perfect recrystallisation in these sediments. For certain reasons, which will be given later, the period between the stoppage of the physical expansion and the final consolidation of the Bulla granodiorite appears to have been considerable, and this may have played some considerable part in effecting the metamorphic changes.

The temperature of crystallization of a granite magma is probably comparatively low, perhaps between 400°C. and 500°C. This low temperature would favour the formation of hydrated minerals such as biotite and prehnite, and amphiboles, in the contact rocks.

3.—Processes in the Differentiation of the Granodiorite.

A. Granodiorite.

There is always considerable difficulty in obtaining equigranular granodiorite free from numerous dark aggregates which are disseminated through it. It has been described by James, and his description will suffice. It might be added that the plagioclase felspars have a composition approximating to $Ab_{60}An_{40}$ in the central zones, but grade to acid oligoclase in the outer zones. The other minerals present are quartz, orthoclase, biotite which is usually more or less chloritized, muscovite, accessory minerals, sericite, calcite and kaolin derived from the felspars. Occasionally pale green aggregates, which do not appear to have any relation to the other minerals, are present. [1682 and 1687.]

5.—V. M. Goldschmidt: "Die Kontactmetamorphose im Kristianiagebiet."

B. Cognate Xenoliths.

These are numerous and of varying size. They are distinguished from accidental xenoliths by their relatively coarse and equigranular texture, and grain size is the only respect in which they differ greatly from the granodiorite. One which in appearance is more basic than the average [1673] shows quartz to be abundant and enclosing smaller crystals of altered plagioclase and biotite flakes. It is doubtful whether the term "basic segregation" can be applied to this specimen.

C. Accidental Xenoliths.

(i.) *Recognizable Hornfels which has undergone slight reaction.*—These rocks have been collected from comparatively fresh boulders of granodiorite in the bed of Deep Creek. They are by no means as common as cognate zenoliths. In thin section [1670 and 1671], they are seen to consist of the usual cordierite-biotite-quartz assemblage, with numerous grains of plagioclase felspar of composition about $Ab_{70}An_{30}$. In one case [1670] there is a single twin of orthoclase enclosing the hornfels minerals, and in the hand specimen such crystals are occasionally seen, exhibiting their faces in a manner similar to felspars of the hornfels impregnated with alkaline solutions, discussed previously. Magnetite is abundant in this rock, and appears to have imparted to some of the cordierite intergrown with it a pale yellow colour and faint pleochroism.

(ii.) *Xenoliths coarser in grain than recognizable hornfels.*—These are rare. They were at first sight mistaken for fine-grained basic cognate xenoliths, but in section [1672] the hornfels assemblage is seen to be present and also oligoclase of composition $Ab_{70}An_{30}$, which forms more than a quarter of the area of the whole section. All the minerals are coarser in grain than the minerals of hornfels and the cordierite has been cleared of its inclusions and exhibits definite cleavage. The size of such xenoliths as have been found does not exceed three inches in length.

(iii.) *Foliated xenoliths.*—These are usually only up to an inch in length. They contain abundant biotite flakes arranged in a more or less parallel fashion, which gives a foliated appearance to the rock. In section they show interesting mineral assemblages. [1674-1678.] When cut parallel to the foliation plane biotite appears as rich red-brown plates. [1674.] In addition, within this section are unzoned plagioclases which appear, however, to vary slightly among themselves in composition. They are more acid than the plagioclase cores of the granodiorite, and have compositions in the neighbourhood of $Ab_{65}An_{35}$. Magnetite is abundant in areas rich in biotite. Cordierite is very abundant as large areas of colourless mineral possessing indistinct cleavage and brilliant yellow pleochroic haloes round minute colourless, highly refracting inclusions. The cordierite is clouded with minute, rod-like inclusions of higher refractive index than their host, and these are without doubt sillimanite. There are also small bottle-green isotropic grains and aggregates having a very high refractive index, and often resembling cubic forms. These are spinels.

Another section [1675] shows pleochroic haloes, sillimanite and spinel excellently developed. Part of the section has the simple cordierite-biotite-plagioclase-quartz assemblage similar to that of type (ii.). Leafy aggregates of muscovite are abundant, and intergrown with these is a pale-green biotite of similar habit, which sometimes is altered to chlorite of a similar colour. This biotite occurs in several sections to be described, and from examination of several basal sections is seen to have a low axial angle. It is weakly pleochroic. Brownish biotite often grades into greenish biotite, being in optical continuity with it. These leafy micas appear to crystallize from pale green aggregates of finer grain. These aggregates often contain "ghosts" of brown biotite merging into them. They also contain numerous olive green pleochroic haloes and exhibit, as a mass, cleavage lines, which are continuous with cleavage lines of adjacent cordierite. From the occurrence of the green aggregates it seems certain that they are derived from cordierite. They are identical with the isolated areas of pale micas seen in the granodiorite itself.

The foliated structure is not always well-defined in the hand specimen, especially in the smaller examples. There is really a transition into the small disseminated aggregates which are described in the next section; a transition type [1676] is seen to have similar mineral associations. Sillimanite is especially well-developed. The brown biotite is particularly clear and differs from the biotite of the granodiorite, which is rather dull in comparison. Part of this section is of the adjacent granodiorite, and a beautiful example of simply-twinned zoned plagioclase, ranging from andesine well towards albite, is present. The characters of the other sections [1677 and 1678] are similar. The spinels of [1678] are grouped in large aggregates.

(iv.) *Small dark aggregates disseminated throughout the granodiorite.*—These seldom exceed ⅜ inch in diameter, and are usually smaller. They form an important constituent of the granodiorite as a whole, and it is almost impossible to select a piece of granodiorite which lacks them. In section [1679, 1680, 1681] they are seen to have similar characteristics to the foliated xenoliths, but the alteration of cordierite has usually proceeded further. The phenomenon of green and brown biotite in optical continuity is particularly well developed [1680], while in one [1681] a large garnet is present. The interstitial cracks of this garnet are filled with green biotite, which is rather darker in colour and more strongly pleochroic than usual.

(v.) *Cordierite Crystals.*—These were at first mistaken for hypersthene or hornblende. They occur as fragments up to half an inch in length, possessing a dark green colour, often rectangular outlines, and one good cleavage. In thin section [1683-1684-1685] this cleavage (parallel to 010) is seen to be perfectly developed, while another cleavage at right angles to it is seen. Pleochroic haloes are well developed, though not very numerous. The pale green micaceous mixture is always abundant, and in addition large portions of the crystals have often changed to serpentine. Traces of this serpentine are also found in the other accidental xenoliths, and it is to this mineral and the green mica that the cordierite crystals, partly altered, owe their colour, and their hornblendic or hypersthenic appearance.

D. Explanation of the Accidental Xenoliths by the Reaction Principle.

This principle and its relation to petrogenesis have been outlined and applied by N. L. Bowen.[6] Briefly, it may be stated thus:—Earlier minerals crystallizing out react successively, as the temperature falls, into minerals of lower temperature formation. A typical reaction in which the change over is continuous, is the plagioclase felspars system. A typical discontinuous series is represented by the series Olivine-Pyroxene-Amphibole-Biotite. In simple igneous rock-magmas these two combine at lower temperatures, and the later members of the combined series are Orthoclase, Muscovite and Quartz. Generally speaking, in both continuous and discontinuous series, if an early member is added to a liquid in equilibrium with a later member, the early member is made over by reaction with the late member. If a late member is added to a liquid in equilibrium with an early member, the late member is melted into the liquid, and the early member crystallizes to supply the heat for melting. Sedimentary rocks are fortuitous in composition, and their minerals do not fit into igneous rock series, but up to a certain extent they may by reaction affect the composition of the phases of an igneous rock which includes fragments of them, without changing their actual phases. Acid magmas in the form of batholiths are probably never superheated, and the great amount of heat extracted in first of all heating the wall rock and inclusions up to the temperature of the magma itself, forbids, to any great extent, the reaction between magma and inclusions.

This principle may now be applied to the xenoliths of the Bulla granodiorite. The cognate xenoliths probably represent the remains of the magma at some previous time, and it is doubtful if the magma was much, if at all, more basic before the absorption of the present accidental xenoliths than it is now. The plagioclase crystallizing out was probably somewhat more acid than $Ab_{60}An_{40}$, as the cores of the plagioclase of the granodiorite

6.—N. L. Bowen: "Reaction Principle in Petrogenesis." Journ. Geol., Vol. XXX., No. 3, 1922. Idem, "The Behaviour of Inclusions in Igneous Magmas." Ibid., Vol. XXX., No. 4, Supplement, 1922.

have this composition, while the plagioclase within the accidental xenoliths is considerably more acid.

The xenoliths of hornfels are probably broken up by mechanical means as they enter the magma, reaction thereby being facilitated. The minerals of the hornfels are quartz, biotite and cordierite. The first two are members of the general igneous rock series, but the last is foreign to this series. Quartz, being the latest member of the reaction series, is melted, while plagioclase more acid than $Ab_{60}An_{40}$ crystallizes, either within the xenoliths, which tend to disintegrate by the removal of quartz, or upon the plagioclase crystals of the granodiorite already formed. The removal of quartz allows the other constituents of the reacting hornfels to come together more in contact with each other, and these unite to form larger crystals, and in extreme cases produce, with cordierite-rich hornfels, almost pure, more or less idiomorphic cordierite crystals.

Cordierite is unstable in contact with the liquid of the magma, and therefore decomposes into muscovite and pale green biotite, the latter being very poor in ferric iron, which indicates that the cordierite was also very poor in this constituent. The decomposition may be represented by the following equation—

$$\underset{\text{Cordierite.}}{(2MgO.2Al_2O_3.5SiO_2)} + 2\underset{\text{Orthoclase.}}{(K_2O.Al_2O_3.6SiO_2)} + 2H_2O$$

$$= \underset{\text{Biotite.}}{(K_2O.2MgO.Al_2O_3.3SiO_2)} + \underset{\text{Quartz.}}{8SiO_2} + \underset{\text{Muscovite.}}{(2H_2O.K_2O.3Al_2O_3.6SiO_2)}$$

The alkaline constituent of the liquid is represented for convenience by the orthoclase molecule. The biotite, in which potash and hydrogen may be isomorphous, is represented as having all potash, which would not be so actually, and likewise ferrous-iron of the biotite and cordierite has been omitted, and the pure magnesian molecules used.

Serpentine may result from cordierite from a reaction of the following nature—

$$3(2MgO.2Al_2O_3.5SiO_2) + 3(K_2O.Al_2O_3.6SiO_2) + 10H_2O$$

$$= 2\underset{\text{Serpentine}}{(2H_2O.3MgO.2SiO_2)} + 11SiO_2 + 3(2H_2O.K_2O.3Al_2O_3.6SiO_2)$$

On complete disintegration and mixing with the magma liquid, this serpentine would be made over to biotite.

$$2(2H_2O.3MgO.2SiO_2) + 3(K_2O.Al_2O_3.6SiO_2) = 3K_2O.2MgO.Al_2O_3.3SiO_2 + 13SiO_2 + 4H_2O.$$

The brilliant red-brown biotite of the xenoliths and occasional included flakes in the cordierite crystals are recrystallized flakes from the original hornfels. This mineral appears also to be adjusting its composition to that of the pale green variety, and hence arise the lighter edges on the brown flakes and the biotite "ghosts" within the pale green aggregates.

Cordierite is a metasilicate while biotite and muscovite are ortho-silicates, hence, as shown by the equations, quartz is liberated; furthermore by crystallization reaction this quartz is melted and removed, along with the quartz of the original hornfels, so that the xenoliths become more basic. We cannot picture the general temperature of a granitic magma as being anywhere near as high as the melting point of cordierite, even though the latter be reduced by the presence of other minerals, so that this mineral cannot melt within the xenoliths, but the temperature being still high and maintained in all probability for a great length of time, reaction can take place. Cordierite decomposes into sillimanite and spinel with a separation of quartz. The quartz is melted off, and the reaction tends to proceed till cooling of the whole mass prevents further reaction, or, the cordierite decomposes entirely into micas. As soon as spinel or sillimanite come in contact with the liquid of the magma they disappear by reaction, as they are only stable within the cordierite itself, and represent products of subsidiary reactions within the xenoliths themselves, which are permitted to act by a process of solid diffusion.

Likewise garnet may be produced by the action of biotite and cordierite, represented roughly by the following equation—

$$(K_2O.Al_2O_3.2MgO.3SiO_2)+2(2MgO.2Al_2O_3.5SiO_2)+2H_2O$$
$$=\underset{\text{Garnet.}}{2(3MgO.Al_2O_3.3SiO_2)}+SiO_2+(2H_2O.K_2O_3Al_2O_3.6SiO_2)$$

E. Effects of Reactions upon the Granodiorite.

From the equations given it will be seen that the effects of reaction have been to fix potash by the formation of micas. This will mean that the liquid is impoverished in this constituent, and when crystallization is complete the orthoclase: plagioclase ratio will be decreased. The crystallization of some plagioclase within the xenoliths will tend to keep the ratio constant, but nevertheless much of the plagioclase probably still crystallizes, as already stated, within the magma itself, on the already formed more basic plagioclase.

The amount of quartz within the liquid will be greatly augmented by the melting out both of original quartz in the hornfels, and that thrown out by the conversion of cordierite to micas.

The muscovite within the granodiorite may have been remelted, according to its position in the general igneous reaction, and again precipitated on the cooling of the magma, but it appears as though the flakes have merely floated into the liquid, with which they are in equilibrium. Therefore it would appear as though muscovite can be in equilibrium with both biotite and orthoclase.

In the more recent xenoliths the only effect has been a slight addition of quartz and subtraction of oligoclase, as the cordierite has not started undergoing reaction. The crystals of orthoclase in the specimen of recognizable hornfels indicate that this block did not fall into the magma until the latter had reached the stage where orthoclase is normally crystallizing.

To sum up, therefore, the only effect that reaction of xenoliths and magma has had upon the latter, has been to decrease orthoclase, increase quartz, and introduce muscovite. This bears out Bowen's contention that, generally speaking, such reaction only varies the relative amounts or individual compositions of phases. The introduction of muscovite occurs, as it can probably coexist with liquids from which biotite and orthoclase can crystallize. In normal differentiation of pure igneous rocks, the alumina content does not reach a high enough value to give muscovite instead of orthoclase, till the very last stages of crystallization.

The cordierite crystals and their relics, and the dark aggregates, are so intimately mixed with the true igneous minerals of the Bulla granodiorite that an analysis will be of both granodiorite and xenoliths. The result will be to increase the percentages of the constituents MgO, FeO, and Al_2O_3. The percentage of SiO_2 will remain fairly constant, as the percentages of this constituent in cordierite-biotite-quartz hornfels and granodiorite respectively, are comparable. The percentage within the granodiorite proper will be larger than indicated by an analysis, as nearly all the quartz now resides in the igneous rock. Following are the analyses of Bulla granodiorite, Harcourt granodiorite (?) and Gellibrand's Hill adamellite. The Harcourt rock is probably fairly typical of Victorian plutonic rocks. For the present purpose accessories are omitted.

	Bulla[7]	Harcourt[8]	Gellibrand's Hill[9]
SiO_2	66.13	70.94	67.75
Al_2O_3	16.83	13.99	16.11
Fe_2O_3	1.11	0.35	0.50
FeO	4.17	3.02	4.00
MgO	1.83	0.80	0.79
CaO	3.26	2.35	2.68
Na_2O	2.25	3.94	2.60
K_2O	3.14	3.66	3.42
H_2O+	1.68	0.21	0.96
H_2O-	0 23	0.11	0.20
Analyst.	F. Watson.	G. Ampt.	H. C. Richards.

The Bulla granodiorite is seen to be richer in FeO and MgO than the Harcourt rock, which is not contaminated with accidental xenoliths. The Al_2O_3 content is also much higher. If the xeno-

7.—"The Physiography and Geology of the Bulla-Sydenham Area," A. V. G. James. Proc. Roy. Soc. Vic., Vol. XXXII. (N.S.), Pt. II., 1920.

8.—"On the Origin and Relationship of Some Victorian Igneous Rocks," H. S. Summers, Ibid., Vol. XXVI., (N.S.), Pt. II., 1914.

9.—"Notes on the Geology of Broadmeadows," F. L. Stillwell, Ibid., Vol. XXIV. (N.S.), Pt. I., 1911.

liths could be excluded from the former it is quite likely that the original rock would have a composition similar to the Harcourt rock. It is of interest to note that in the Gellibrand's Hill adamellite, in which dark aggregates appear to be far less numerous than in the Bulla granodiorite, and among the contact rocks of which, so far as can be made out on the surface, cordierite rocks do not appear, the MgO, FeO, Al_2O_3 contents are lower.

The granite of Big Hill, south of Bendigo, and the granodiorite of Mornington, are uncontaminated rocks, so far as their present textures and mineral contents indicate, and the contact zones of both are siliceous and lacking apparently in cordierite rocks. Whether this is merely coincidence or whether there is some significance in the fact, in the light of the contamination of the Bulla rocks, seems obscure. It would be interesting to know whether all contact zones rich in cordierite have had similar effects on the igneous rock.

In one case this is proved to be so, for at Trawool, where cordierite hornfels identical with that of Bulla is abundant in the contact zone, the intruding adamellite contains dark aggregates and cordierite crystals, one of which is seen in thin section [1686] to have properties identical with those of Bulla.

The small aggregates are very numerous throughout the granodiorite. The foliated xenoliths are not very common, while the recognizable hornfels and those a little more altered are rare. It would appear, therefore, that the small xenoliths may have belonged originally to one crop of included hornfels blocks, and since then but little inclusion of wall rock by the invading magma has taken place. This could be accounted for by a stoppage of the magma's upward and outward expansion by dynamical means after the crop of included fragments now represented by the small aggregates, had been engulfed. This phenomenon has been considered earlier in the paper to have been one factor in intensifying metamorphism, by the continuous conduction of heat through the same wall rock sediments during the period of further recrystallization.

The change of cordierite to micas is exothermic, and hence the magma regains some of the heat which it expended in forming cordierite from chlorite and sericite. This heat of reaction may have an appreciable effect in prolonging the time of final consolidation and cooling of the magma.

In describing the effects of alkaline material on cordierite-biotite-quartz hornfels by impregnation with the last stage aqueous juices of the magma, earlier in the paper it was shown that cordierite passed to serpentine and biotite to magnetite. Biotite was evidently unstable in contact with the liquid of the alkaline magma of the vein, and so passed to magnetite which seems to play a more or less neutral role in the general reaction series. Cordierite passes directly to muscovite and serpentine, the latter evidently being a very late member of a ferro-magnesian series.

4.—Summary and Conclusions.

The metamorphic contact zone at Bulla consists mainly of cordierite-biotite-quartz hornfels which are the outcome of chemical rearrangement and recrystallization of quartz-sericite-chlorite mixtures. Quartzites and sericite-biotite-quartz hornfels occur, and also lenticles of lime-silicate hornfels containing what may be prehnite, and also diopside.

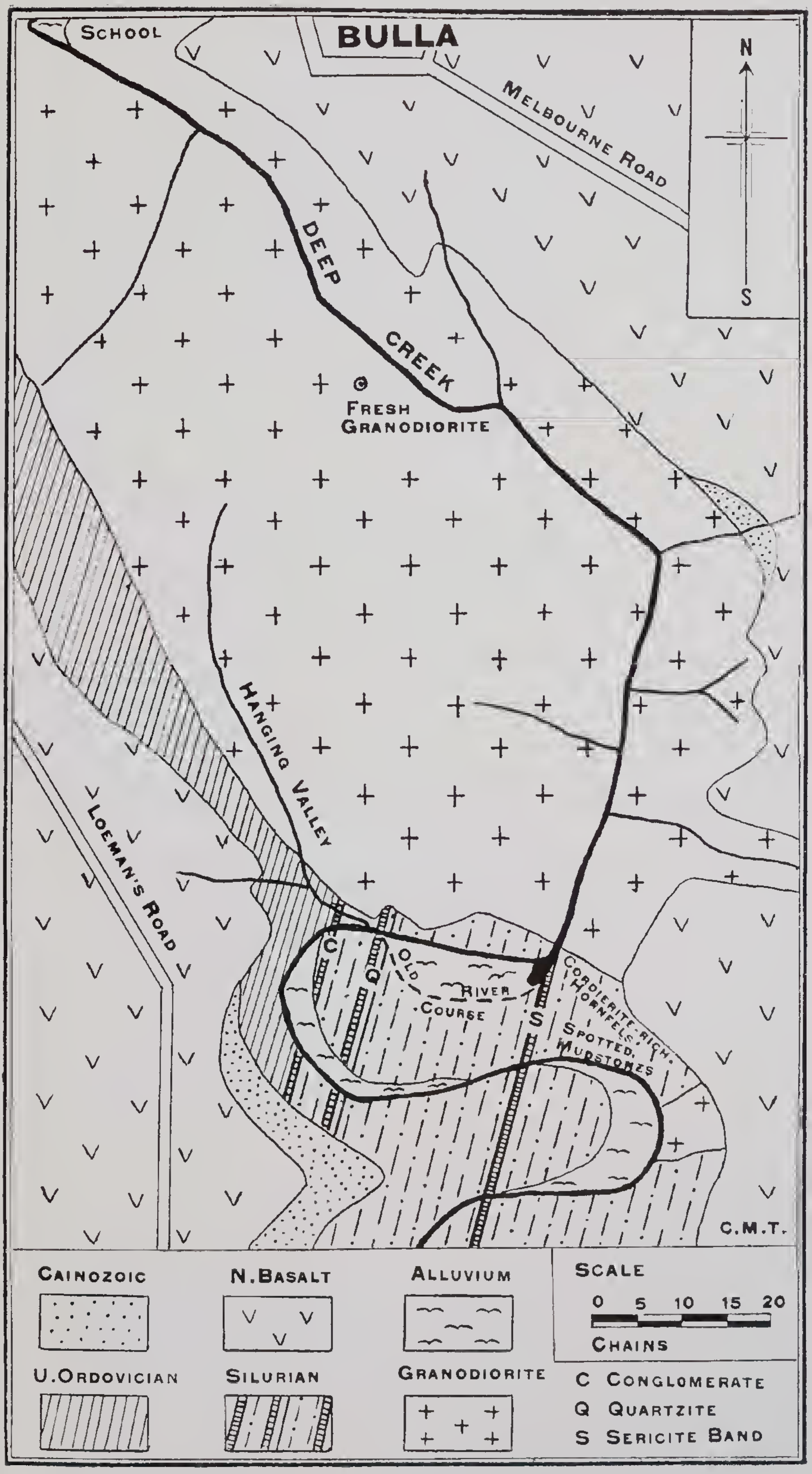
Pneumatolysis appears to have played but a small part in the recrystallization processes, but a long sustained heating of a naturally reactive mixture, naturally reactive in virtue of its heterogeneous chemical composition and water content, has probably been the cause of metamorphism.

Of interest is the vein of alkaline minerals threading through and impregnating the hornfels. It is connected with the pneumatolytic stage of the magma, but has not had an effect of intense recrystallization of the hornfels, but has reacted with the hornfels and decomposed the biotite and cordierite of the latter.

The prevalence of hydrated minerals and of amphiboles in the contact zone indicates that the temperature of metamorphism was not high.

The microscopical examination of the Bulla granodiorite shows it to be contaminated with disseminated fragments of rocks containing minerals, some of which are foreign to igneous rocks. These fragments are in the form of foliated xenoliths, smaller dark aggregates, and crystals, more or less idiomorphic, of cordierite. By the application of the reaction principle, the mineralogical associations of the xenoliths and the effect of their reaction upon the granodiorite are best accounted for. The cordierite of the xenoliths breaks up by reaction into muscovite and a pale green biotite. The muscovite is disseminated into the still liquid portion of the magma, with which it appears to be in equilibrium. The biotite of the xenoliths also tends to change over into this green form. Serpentine is also formed from the cordierite, but probably ultimately reverts back to biotite. The fixing of alkali by the xenoliths involves a decrease in the amount of orthoclase in the completely crystallized granodiorite. Quartz which at the time of reaction must be in the liquid phase, is melted out of the xenoliths, and plagioclase crystallizes within the xenoliths, or as more acid zones on previously crystallized plagioclase. The depletion of quartz within the xenoliths results in their becoming more basic, and cordierite tends to break down into sillimanite and spinel with the liberation of quartz, which is melted off, until the lowering of temperature of the whole mass checks further reaction. Biotite and cordierite may react to give rise to garnet.

In analysing the granodiorite, all small xenoliths and cordierite crystals could not be excluded, and hence the analysis is of contaminated rock, and not pure igneous rock. On this account the Bulla granodiorite is relatively high in MgO, FeO and Al_2O_3.



Geological Map of Area South of Bulla, Victoria